Algorithmic Infrared Correction for CMOS Color Sensors

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Abstract

Electronic image processing has become a key in modern data application. The field of accurate image acquisition is most important in respect to all further processing steps. Image sensors based on CMOS technology show a high potential compared with currently dominating CCD (Charge Coupled Device) technology. But one disadvantage of CMOS image sensors is its high affection to infrared light. This influence is maleficent especially for color sensors, where specific color information is destroyed by this disturbances. Traditional infrared cancellation methods using additional infrared filters in the optical sensor path are quite expensive compared with the cost of the CMOS sensor itself, so less expensive methods are needed. This problem is investigated by introducing a new algorithmic infrared correction method which can be easily integrated to traditional sensor design. This approach is demonstrated on a sensor with modified Bayer mosaic color filter for red, green, blue and infrared detection. But it is also extendable to other designs/technologies. Finally, we will derive design methods for improved multi channel color sensors and show examples and simulation results.

1 Introduction

1.1 Conventional Color Image Aquisition

The human visual system is an integral part in the theory of color. The vision of color is the perceptual result of light in this visible region of the electromagnetic spectrum, having wavelengths from about 400 nm to 700 nm, incident upon the retina. There are three types of color photoreceptor in human retina, called cones, which respond to incident radiation with different spectral response functions. A fourth type of photoreceptor cell, the rod, is also present in the retina. But rods are effective only at extremely low light levels and (although important for vision) do not play a significant role in human color image reproduction.

Because there are three different types of color photoreceptors, three numerical components are necessary for a comprehensive description of color and three numerical components are also sufficient providing that appropriate spectral weighting functions are used for detection. This functions has been the concern of the science of colorimetry which analysed and quantified the properties of human perception. In 1931, the Commission Internationale de L'Éclairage (CIE) adopted the first standard functions for a hypothetical Standard Observer, that specifies the transformation of a spectral power distribution (SPD) into a set of three numbers that specifies a color [1]. This triple of numerical components define mathematical coordinates of the color space and there are a variety of different representation for color space specification, including CIE XYZ, CIE xyY (Fig. 1[1]), CIE L*u*v*, CIE L*a*b* or device-dependent RGB, HSV, YIQ and so on.

1. All images presented in this paper are available in color at http://www.iee.et.tu-dresden.de/~henker/pdf/moc2001.pdf

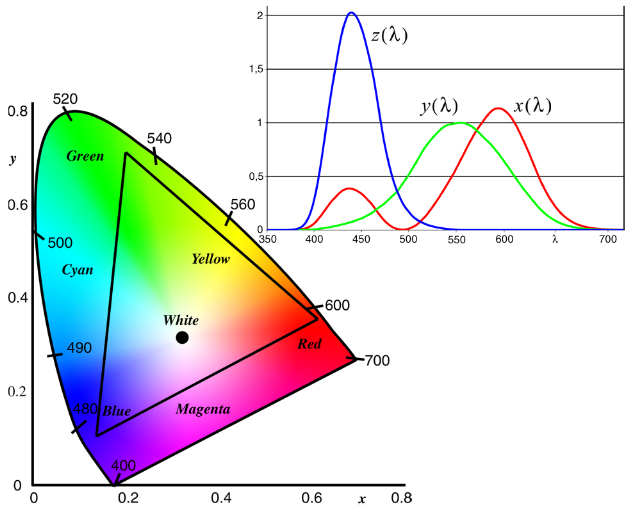

Fig. 1 CIE xyY color space with RGB triangle and CIE XYZ Standard Observer

Current implementation of color sensors are almost directly based on this tristimulus theory. Most image sensor and photographic devices exclusively use a set of three photoactive elements. Each element i has a specific spectral sensitivity $s_i(\lambda)$, resulting from the combined characteristics of photo material and color filter (if exist) implementing following equation:

$$S_i = \int P(\lambda) \cdot s_i(\lambda) d\lambda \qquad \text{eq. 1}$$

where $P(\lambda)$ is the spectral power distribution of irradiated light and S_i is the resulting color component. The characteristic of $s_i(\lambda)$ implements often directly a RGB color space and thus is bound to CIE standard functions. Basically it has to mimic the spectral response function of the human eye in order to reproduce an image as human. But under technical constraints a comprehensive representation is not entirely possible. In order to reduce the resulting errors in color a wide range of color correction schemes were developed. But usually the assumption is made that a precise correction is possible only on base of this defective tristimulus sensor data. According to this premise a specific sensor output is always correlated with a specific color. In many cases the color rendition is analyzed and optimized for few examples under idealized condition and the remaining color space is interpolated. Many methods are described for practical realization, i.e. look-up tables or more or less nonlinear mathematical approaches [2].

1.2 CMOS Sensor Specifics

The currently dominating image sensor technology is CCD (Charge Coupled Device). It is specially designed for image acquisition and thus has very good properties in this terms although it requires special manufacturing lines. But logic integration for i.e. data preprocessing is not possible. Compared with CCD, CMOS technology has a lot of advantages. It is cheap, manufacturing has no special requirements and further it is possible to integrate the sensor together with data processing circuitry on the same chip. Sensors with integrated controller, A/D-converter and additional processing units denote extremely reduced costs for manufacturing and also reduced power dissipation which is most important especially for mobile applications (Fig. 2, [3]). But one disadvantage of CMOS sensors compared with CDD is especially the spacial distributed noise of all active sensor elements, called „Fixed Pattern Noise“. Possible correction methods are i.e. correlated double sampling (CDS), current-mode signal processing, special A/D converter techniques and algorithmic correction schemes [4]. Image preprocessing including color correction, filtering etc. can be integrated as well.

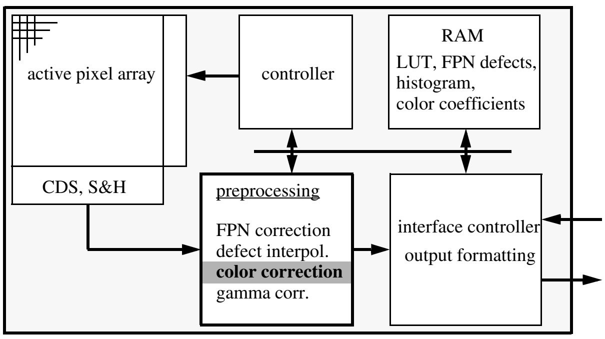

Fig. 2 Single-Chip CMOS-sensor architecture

On side of image acquisition the main disadvantage of CMOS sensors is their affection to infrared light. The influence of infrared light is destructive especially to color sensors, where specific color information is disturbed by this influences. Traditional infrared cancellation methods using additional infrared filters in the optical sensor path are quite expensive and are also not able to shield all infrared disturbances from the sensor. Conventional tristimulus color correction schemes are not able to determine image errors caused by infrared influence because natural images can be affected by infrared light in various ways, i.e. green leaves of living plants are reflecting infrared light as well as different synthetic materials of various colors. There is no correlation between a specific tristimulus sensor output and the amount of infrared light absorbed by the sensor, in fact there is not even detectable correlation with infrared irradiation at all. This can be proven easily by analysing eq. 1: If all $s_i(\lambda)$ contain spectral components not related to i.e. CIE specification, the resulting S_i can be only corrected when the amount of the interference itself is known. This is not possible if the sensor generates only a tristimulus value set because they all contain information directly related to color. Since of the high complexity of possible infrared sources in natural images assumptions of hypothetical correlations between image components and infrared disturbances are not feasible. Therefore conventional correction method will fail. This methods would instantly affect the color rendition. The conclusion is that three channels are not sufficient for infrared detection on CMOS sensors. That intends for algorithmic correction an additional channel, meaning an additional sensor element is necessary.

2 Spectral Color Correction

2.1 Modified Bayer Mosaic

Our approach for infrared correction will be demonstrated on a traditional sensor design using a Bayer color filter array (CFA). Bayer CFA is widely used on current color image sensors and consist of a four pixel square with color filters for red/green and green/blue as illustrated in Fig. 3a. To enable infrared correction with inconsiderable effort we propose only a minor modification. As mentioned, an additional sensor element for infrared detection is necessary. Since direct infrared detection is complicated and does not fit technical constrains of usability and low costs, an indirect detection method is proposed. The color sensor elements are basically characterized by their color filters and an additional color channel can be easy realized by an element with no color filter. Our suggestion is to use one of the two green sensitive sensor fields of Bayer mosaic by leaving out the color filter (Fig. 3b).

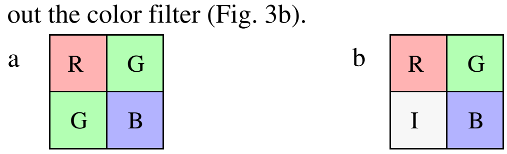

Fig. 3 Original (a) and modified Bayer mosaic (b)

2.2 Spectral Correction Method

The defective sensor outputs S_j can now be transformed to a standard color space. The used color space representation can be defined by the CIE Standard Observer (i.e. CIE XYZ or device dependent RGB). To achieve the best reconstruction A'_i of an color space coordinate A_i from N sensor outputs S_j a linear combination can be used.

$$A'_i = \sum_{j=1}^{N} c_{ji} \cdot S_j \qquad \text{eq. 2}$$

This is obviously possible because of eq. 1, when

$$A'_i = \sum_{j=1}^{N} c_{ji} \cdot \int_{\lambda} P(\lambda) \cdot s_j(\lambda) \cdot d\lambda$$

$$= \int_{\lambda} P(\lambda) \cdot \sum_{j=1}^{N} c_{ji} \cdot s_j(\lambda) \cdot d\lambda \qquad \text{eq. 3}$$

where s_j are the spectral response functions of the sensor implementation. It follows that if:

$$a'_i(\lambda) = \sum_{j=1}^{N} c_{ji} \cdot s_j(\lambda)$$

$$A'_i = \int_{\lambda} P(\lambda) \cdot a'(\lambda) \cdot d\lambda \qquad \text{eq. 4}$$

where $a'_i(\lambda)$ is the best reconstruction of an ideal color space spectral response function $a_i(\lambda)$.
To determine the coefficients c_{ji}, the method of least square error is used, so the approximation error

$$F = \int (a_i(\lambda) - a'_i(\lambda))^2 d\lambda$$

is minimized. The solution is given by

$$\int a_i(\lambda) \cdot s_k(\lambda) d\lambda = \sum_{j=1}^{N} c_{ji} \cdot \int s_j(\lambda) \cdot s_k(\lambda) \cdot d\lambda$$

$$\text{for } k = 1 \ldots N \qquad \text{eq. 5}$$

Thus for each color space coordinate i with spectral response function $a_i(\lambda)$ a set of N coefficients c_{ji} can be found to derive the best approximation $a'_i(\lambda)$ with minimized L2-norm. It is also possible to use other spectral response functions for estimation with this method i.e. the infrared response which leads to a complete new field of applications (visual enhancement, night vision camera etc.) For better approximation of human vision it is also possible to choose a color model more adjusted to the human eye, i.e. CIE L*a*b*, which represents the logarithmic characteristic of the eye with a polynomial approach. But this requires a more sophisticated nonlinear optimization method.

2.3 Application concept and simulation

For visual test a sensor simulation toolkit was designed, which models a simple optical path with different light source, a sensor of given characteristic and a color correction module. A CIE standard system is implemented for comparison as well. The application concept of the algorithmic infrared correction method was testified on data from a single-chip CMOS color video sensor, basically consisting of a sensor array with CFA and circuitry for gamma correction, video signal generation etc. [5]. The characteristics of the CFA was designed for CCD, so the image quality without color correction is expectedly not very well. Our correction method is also able to improve color reproduction. The spectral sensitivity functions of the sensor was measured and corrected using the CIE XYZ color space as reference. The results are shown in Fig. 4 and indicate a reasonable approximation for Y and Z coordinates except for minor divergences. But the X coordinate still is affected by infrared disturbances. This is because the sensor elements cannot separate the spectral range from 600 to 800 nm to allow a better correction in this area. Regardless the approximation errors are between 5 and 15% visual picture quality is comparable with consumer CCD which show color rendition errors of similar amount. Comparison images from a simulation are shown in Fig. 5.

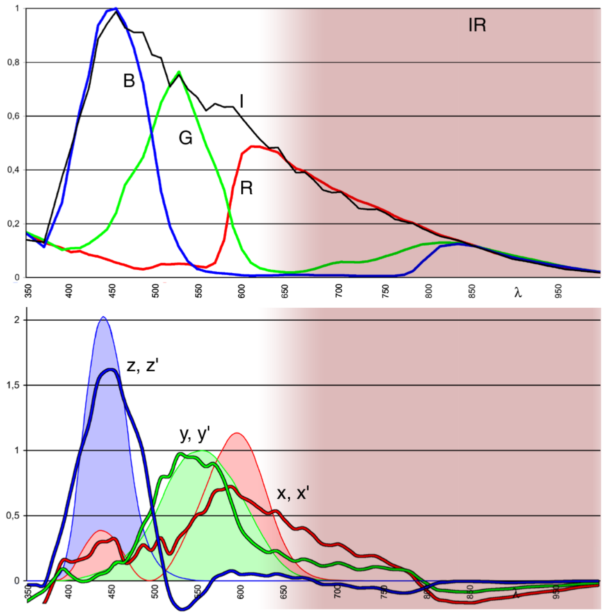

Fig. 4 **CMOS color sensor: measured spectral response (above), corrected functions with CIE XYZ for comparison (below)**

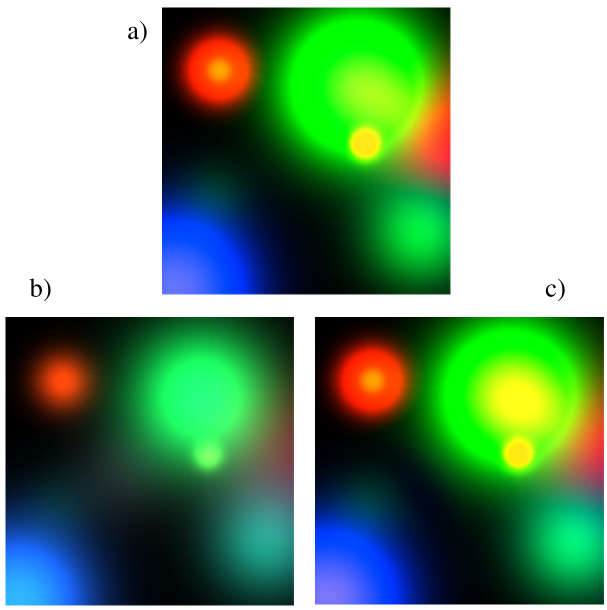

Fig. 5 **Simulation results:**

a) Reference image using CIE XYZ color space definition for acquisition.
b) Sensor image without color correction
c) Sensor image with correction according spectral sensitivities from Fig. 4

For a better approximation in our example the color separation of the sensor has to be improved, i.e. by enhanced CFA characteristics. At least this result has proven that color filters designed for CCD are not suitable for CMOS sensors. Another method offering better color rendition even with uncritical CFA parameters can be obtained by an increased number of color channels.

2.4 Multi color sensors

Because of general differences between the spectral sensitivitys of color sensitive detectors and the human eye, color reproduction is generally affected by errors. The basic presumption of sufficiency of tristimulus color image sensors is superseded under the this circumstances. As stated above tristimulus based color correction methods are not able to eliminate systematic errors in color. Algorithmic correction methods (i.e. according eq. 5) based on spectral sensitivity can at least find optimized solutions.

Our method of spectral reconstruction can further be extended to achive human like vision under current technical feasibilities. By using sensors with more than three color channels per pixel the color rendition can be highly improved. These multi color sensors are currently under research and show high potential. Researches on multi spectral image sensors confirm by far better results compared with conventional tristimulus image sensors [6]. Multi color sensing is i.e. already used in the field of photography: the New-Reala technology by Fuji uses four light-sensitive emulsion layers for better color reproduction. In order to achieve improvements the spectral sensitivities of the sensor do not require special characteristics. It is sufficient if the spectral functions are independent and able to separate the spectral region of interest.

An example of a 6-channel color sensor with hypothetical spectral sensitivities is shown in Fig. 6. The approximation error for this example is below 0.5% and the difference between an ideal CIE system and the approximation is by far smaller than usual quantization noise would be.

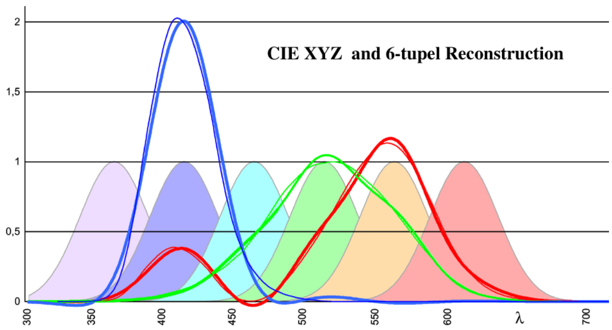

Fig. 6 **6-tupel reconstruction example**

3 Further developments

Another vulnerability of arrays of color sensor cells exists in its sensitivity to color moiré caused by their spatial arrangement. This effect is part of the underlying principle and cannot be eliminated completely. The elements which are forming a planar color pixel have slightly different positions on the sensor array resulting in color disturbances especially for high spatial frequencies which are recurrent in natural images. An usual compensation method is the use of optical diffusion filters but a negative side effect is the reduction of optical resolution. Another possible approach to decrease this effect is the usage of optimized combinations of colors and their position on the sensor matrix. This is especially promising for multi color sensors where a resulting color triple is generated from a larger number of components (Fig. 7). But this approach needs further investigations. Special adopted filter algorithms can additionally reduce color moiré to a minimum without affecting the spatial resolution of the sensor.

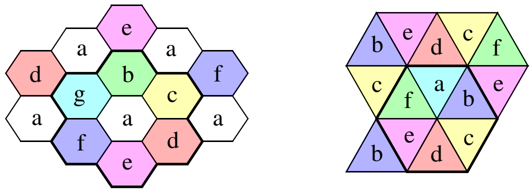

Fig. 7 **CFA mosaic examples for a 7-channel (hexagonal) and a 6-channel (trigonal) sensor**

4 Conclusion

A method for algorithmic correction of infrared disturbances on CMOS color sensors was presented. Results of practical examples show achievable quality comparable with consumer CCD systems. Possible applications and simulation results were shown. The application of this method can further be extended to color correction improvement on general image sensor devices.

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